

CLAIMS

What is claimed is:

1. A microfluidic module comprising:

a flow path comprised of a channel formed in a first substrate and enclosed by a second substrate, the flow path having a fluid inlet and a fluid outlet;

mixing structures in the flow path; and

one or more independently controlled heat exchangers in thermal contact with the flow path for conditioning a nanocrystal forming reagent within the flow path; the flow path inlet receives the nanocrystal forming reagent and conditioned nanocrystal forming reagent is removed from the flow path at the outlet, the flow path inlet and outlet capable of forming a fluid tight seal with one or more controlled fluid delivery devices.
2. The microfluidic module of claim 1 having multiple flow paths.
3. The microfluidic module of claim 1 further wherein the heat exchanger includes an optical source of energy.
4. The microfluidic module of claim 1 wherein the flow path further includes sensors chosen from the group consisting of: particle size sensor, pressure, flow, reagent chemical composition sensing, the sensor output used as an input to a controller for open or closed loop control or said microfluidic module.
5. A microfluidic module of claim 1 wherein the controlled heat exchanger includes a temperature sensor, a heat exchanger, and a controller.
6. The microfluidic module of claim 1 wherein one or more of the independently controlled heat exchangers thermally preconditions the nanocrystal forming reagent.

7. The microfluidic module of claim 1 wherein the first substrate includes one or more thermal isolation structures whereby the flow path is separated into one or more thermally isolated sections.
8. The microfluidic module of claim 1 wherein one or more additional ports are provided at intervals along the flow path for the purpose of adding reagents to modify the shapes, surface coating, and/or sizes of the growing nanocrystals, the one or more ports located between the inlet and outlet of the flow path and capable of forming a fluid tight seal with one or more controlled fluid delivery devices.
9. The microfluidic module of claim 1 wherein the mixing structure mixes multiple flow streams uniformly by dividing the flow stream into multiple smaller streams, the smaller streams being mixed and reacted and recombined with the aid of mixing and thermal equalization structures internal to the flow path or paths.
10. The microfluidic module of claim 1 wherein said flow path includes a particle size sensor wherein fluorescent emission from said particles is utilized in open or closed loop control of temperature or fluid flow in the flow path.
11. The microfluidic module of claim 1 wherein the flow path includes a nucleation section whereby nucleation of nanocrystals occurs during a flow process, said nucleation section including a nucleation length of channel in the flow path, said one or more heat exchangers maintaining said nucleation section at a nucleation temperature, the nucleation section having an inlet in the flow path for receiving a one or more nanocrystal nuclei- forming reagent fluids and an outlet in the flow path for removing nucleated nanocrystals from the nucleation section.
12. The microfluidic module of claim 1 wherein the flow path includes a growth section whereby growth of nanocrystals and/or nucleated nanocrystals nuclei or nanocrystals occurs during a flow process, said growth section including a growth length of channel in the flow path, one or more ports for adding nanocrystal forming reagents, said one or more a heat exchangers maintaining the growth

section at a growth temperature, the growth section having an inlet in the flow path for receiving a nanocrystal forming reagent fluid, and an outlet in the flow path for removing nanocrystals from the growth section.

13. The microfluidic module of claim 1 wherein the flow path includes a growth termination section in which growth of nanocrystals is terminated during a flow process, said growth termination section including a growth length of channel in the flow path, said one or more heat exchangers maintaining the growth termination section at a growth termination temperature, the growth termination section having an inlet in the flow path for receiving nanocrystals in a reagent and an outlet in the flow path for removing nanocrystals from the growth termination section.
14. The microfluidic module of claim 1 wherein the flow path further comprises a purification section whereby phase separation or exchange of fluids containing nanocrystals from fluids occurs during a flow process, said purification section including a separation device in a length of channel in the flow path, said one or more heat exchangers maintaining the purification section at a purification temperature, the purification section having an inlet in the flow path for receiving nanocrystals in a reagent and an outlet in the flow path for removing nanocrystals from the purification section.
15. The microfluidic module of claim 1 wherein the flow path includes a coating section in which a coating is formed on a stabilized nanocrystal in a flow process, said coating section including a heat exchanger for maintaining the coating section at a coating temperature, at least one coating section inlet in the flow path for receiving nanocrystals and coating forming reagent, and at least one coating section outlet in the flow path for removing coated nanocrystals from the coating section, the growth section inlet and outlet capable of forming a fluid tight seal with one or more controlled fluid delivery devices.

16. The microfluidic module of claim 1 comprising one or more sections chosen from the group consisting of nucleation, growth, growth termination, purification, and combinations of these in the flow path on a substrate.
17. A microfluidic module comprising:
- a first flow path comprised of a channel formed in a first substrate and enclosed by a second substrate, the first flow path having a fluid inlet and a fluid outlet;
- a separation device in the flow path for removing impurities from nanocrystals in a fluid, the first flow path inlet receiving nanocrystals in a fluid, said separation device removing impurities from the nanocrystals in the fluid and the first flow path outlet for removing the nanocrystals from the flow path, the flow path inlet and outlet capable of forming a fluid tight seal with one or more controlled fluid delivery devices; and
- a port in the first flow path.
18. The microfluidic module of claim 17 wherein the separation device includes a porous membrane through which the nanocrystals are prevented from passing and fluids are allowed or caused to be exchanged by cross-flow, counter-flow, or co-flow from a second fluid path separated from said first flow path by said membranes.
19. The microfluidic module of claim 17 wherein the separation device includes a porous membrane having pores in said membrane that permit the passage of dispersed nanocrystals.
20. The microfluidic module of claim 17 wherein the separation device contains a semiconductor membrane with internal pore dimensions modulated in order to cause nanoparticles to pass through by means of a drift ratchet property.

21. The microfluidic module of claim 17 wherein the separation device contains membranes that can be caused to be hydrophilic or hydrophobic by means of the application of a voltage.
22. The microfluidic module of claim 17 wherein the separation device includes a porous membrane made from semiconductors, silica glass, metal oxides or polymers.
23. The microfluidic module of claim 17 wherein the separation device includes a porous membrane and the first flow path is in fluid communication through the membrane with a second flow path, said second flow path having an inlet and an outlet, wherein the second flow path contains a device to pulse the pressure of the fluid in the first flow path.
24. The microfluidic module of claim 17 wherein the separation device contains a piezoelectric, magnetic or optical means of inducing sonic or ultrasonic waves in the first flow path for the purpose of separately manipulating nanocrystals in the fluid.
25. The microfluidic module of claim 17 wherein the separation device includes a porous membrane and the first flow path is in fluid communication through the membrane with a second flow path, said second flow path having an inlet and an outlet.
26. A microfluidic reactor comprising:

a flow path including one or more fluidly connected microfluidic modules for making nanocrystals in a flow process, the flow path in each module is a channel formed in at least a first substrate and enclosed by at least a second substrate, said channel in thermal contact with one or more independently controlled heat exchangers along the flow path for conditioning a nanocrystal forming reagent fluid in the flow path, each module having an at least one inlet in the flow path for receiving the reagent fluid and at least one outlet in the flow path for removing

conditioned reagent fluid from the module, each said inlet and outlet capable of forming a fluid tight seal with one or more fluid delivery devices.

27. The microfluidic reactor of claim 26 comprising one or more flow paths.
28. The microfluidic reactor of claim 26 comprising microfluidic modules with one or more inlets, outlets, or combinations of these.
29. The microfluidic reactor of claim 26 wherein the modules are connected in a manner to include parallel, series, or a combination of these.
30. The microfluidic reactor of claim 26 wherein a microfluidic module includes a reagent preconditioning section, a nucleation section, a growth section, and a growth termination section.
31. The microfluidic reactor of claim 26 wherein the channel flow path includes a mixing structure.
32. A method of making nanocrystals comprising:

conditioning nanocrystal forming reagents in a flow path, said flow path including one or more fluidly connected microfluidic modules for making nanocrystal product in a flow process, the flow path in each module is a channel formed in a first substrate, said channel in thermal contact with one or more independently controlled heat exchangers and mixing structures along the flow path to condition the nanocrystal forming reagents in the flow path; each module having an inlet in the flow path for receiving the nanocrystal forming reagent fluid and an outlet in the flow path for removing conditioned reagent fluid from the module, each said inlet and outlet capable of forming a fluid tight seal with one or more controlled fluid delivery devices; and

monitoring a detectable property of said nanocrystal product or reagent in a portion of the flow path and adjusting a controllable heat exchanger, a fluid delivery device, reaction time, or a combination of these to maintain the detectable property of the nanocrystal product in a pre-determined range.

33. The method of claim 32 wherein the nanocrystals forming reagents are fluorescent nanocrystal forming reagents.
34. The method of claim 32 wherein the mixing structures within the flow path divide and recombine the fluid flow of the nanocrystal forming reagents.
35. The method of claim 32 further including the act of purifying the conditioned nanocrystal forming reagents in the flow path.
36. The method of claim 32 comprising one or more flow paths.
37. A method of purifying nanocrystals comprising:

providing nanocrystals in a fluid into the flow path of a microfluidic module having a separation device in the flow path of said microfluidic module, and

separating an impurity from said nanocrystals within said microfluidic module.
38. The method of claim 37 wherein the impurity is a coordinating ligand, a solvent, nanocrystal forming reagents, particles, and combinations of these.
39. The method of claim 37 further comprising the act of providing a second fluid to the flow path from one or more ports along the flow path.
40. The method of claim 37 the separated impurity is a first ligand attached to the nanocrystals that is exchanged for a second ligand to be attached to the nanocrystals in the fluid.